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ESSEX - DIAMOND ORE RESEARCH PROGRAM. THE DEVELOPMENT AND MANUFACTURE OF A GELLED NITROMETHANE EXPLOSIVE FOR PROJECT ESSEX

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California University

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ESSEX - DIAMOND ORE RESEARCH PROGRAM

The Development and Manufacture of a Gelled Nitromethane Explosive for Project ESSEX

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10 October 1974

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A nitromethane-based explosive was formulated that can be pumped and whose gel structure will uniformly suspend 10 wt% sand for several weeks. Safety and performance characteristics were determined. A 907-kg (1-ton) quantity was manufactured, emplaced 6 m (20 ft) underground, and successfully fired in a cratering experiment at Fort Peck, Montana. An additional quantity of 42638 kg (47 tons) was manufactured and test-fired in similar experiments with larger charges conducted at Fort Polk, LA. This explosive has stable and predictable detonation characteristics and can be mixed and pumped in large quantities using equipment fabricated from readily available commercial items.

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SUMMARY

A nitromethane-based explosive was formulated that can be pumped and whose gel structure will uniformly suspend 10 wt% sand for several weeks. Safety and performance characteristics were determined. A 907-kg (1-ton) quantity was manufactured, emplaced 6 m (20 ft) underground, and successfully fired in a cratering experiment at Fort Peck, Montana. An additional quantity of 42 638 kg (47 tons) was manufactured and test-fired in similar experiments with larger charges conducted at Fort Polk, Louisiana. This explosive has stable and predictable detonation characteristics and can be mixed and pumped in large quantities using equipment fabricated from readily available commercial items.

PREFACE

The work documented in this report was done by the Organic Materials Division of the Chemistry Department of the Lawrence Livermore Laboratory under the Defense Nuclear Agency's Project ESSEX, Subtask L19CAXYX971, and by the Office, Chief of Engineers, under Research and Development Project 4AO62118A880 in conjunction with the U.S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory. The explosive selection and testing was an integral part of Project ESSEX. A reliable equation of state for the explosive was required for use in computer code calculations while the fallout tracer studies required that the explosive be capable of suspending sand particles. Field operations required that a safe, reliable mixing and pumping system be developed.

The authors would like to thank CPT Howard H. Reed, U.S. Army Corps of Engineers, for his overall assistance in meeting the required time schedule for the test shots. They would also like to acknowledge the work of Ed Lee in providing equation of state parameters, and Don Ornellas for performing gap tests. Finally, they would like to thank the Site 300 Chemistry Group including John Hallam, Bill Gummer, Gordon Moody, Lee Frahm, and Billy Eskue for help in preliminary testing of the processing equipment.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names is intended to describe the experimental setup, and does not constitute an official endorsement or approval of the use of such commercial products.

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SECTION 1
INTRODUCTION

For over two years, the Lawrence Livermore Laboratory Chemistry Department's Organic Materials Division has worked with the U.S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory (EERL) on explosives problems associated with Projects Diamond Ore and ESSEX. Project Diamond Ore, jointly funded by the Office of the Chief of Engineers (OCE) and the Defense Nuclear Agency (DNA), was a program designed to determine the cratering equivalence of chemical and nuclear explosives. EERL had overall supervision of the project, and LLL's Organic Materials Division provided technical assistance for the chemical explosive. Specifically, the Organic Materials Division was to aid in the selection of an explosive and to determine a useful equation of state (EOS) for the detonation products of the explosive to be used in Project Diamond Ore.

The initial explosive selected as the Diamond Ore high explosive (HE) was a variation of a commercial blasting agent, an aluminized ammonium nitrate slurry. Anomalous behavior or this HE was observed in three explosive cratering experiments completed at Fort Peck, Montana. In one experiment a uniform detonation was observed from rate sticks, the detonation gradually accelerating from the center of the cavity to the wall. Rate sticks in the second shot showed no detonation, but apparently an explosion occurred at late times. In the third experiment the top and bottom hemispheres detonated at different rates. The Montana experiments had 10 wt% sand (125-175 μm in diameter) uniformly mixed in the explosive to conduct tracer experiments. Although inhomogeneity and marginal initiation problems in the explosive were strongly suspected, there was no clear evidence to establish the cause of the erratic behavior.

A number of scaled copper cylinder and aluminum hemisphere shots were then fired with this HE, in both pure and sand-loaded form, the largest containing over 181 kg (400 lb). The detonation velocity

and metal acceleration information obtained from these shots indicated that a meaningful EOS could not be obtained without more extensive testing and evaluation.[1]

In view of this difficulty with the initial Diamond Ore explosive, other explosives were considered for Project ESSEX, the new designation for the continuation of the Diamond Ore program. A nitromethane-based explosive seemed appropriate because nitromethane has a well-defined EOS and will detonate reproducibly at dilutions as high as 40 vol%. It also has potential advantages of economy and ease of emplacement. Work was accordingly started on a gelled nitromethane HE that could accommodate the 10 wt% tracer sand. This report describes the development and manufacture of the explosive and summarizes its characteristics.

SECTION 2
PRELIMINARY EXPERIMENTS

2.1 Formulation

General Mills has recently introduced a modified quar gum, Gengel-512, that is specifically suited for gelling primary nitroparaffins.[2,3] Preliminary test formulations established that approximately 3 wt% Gengel-512 guar gum in nitromethane forms a firm gel that will suspend sand for several weeks. A formulation containing 87/10/3 wt% nitromethane/sand/guar gum was chosen for further study. This composition is called RX-01-AE.

2.2 Safety Data

2.2.1 DTA, Drop Hammer, Ignition and Burn Tests

Differential thermal analysis (DTA) tests on RX-01-AE showed a large endotherm due to evaporating nitromethane. No exotherms were observed, as can be seen in Figure 2.1.

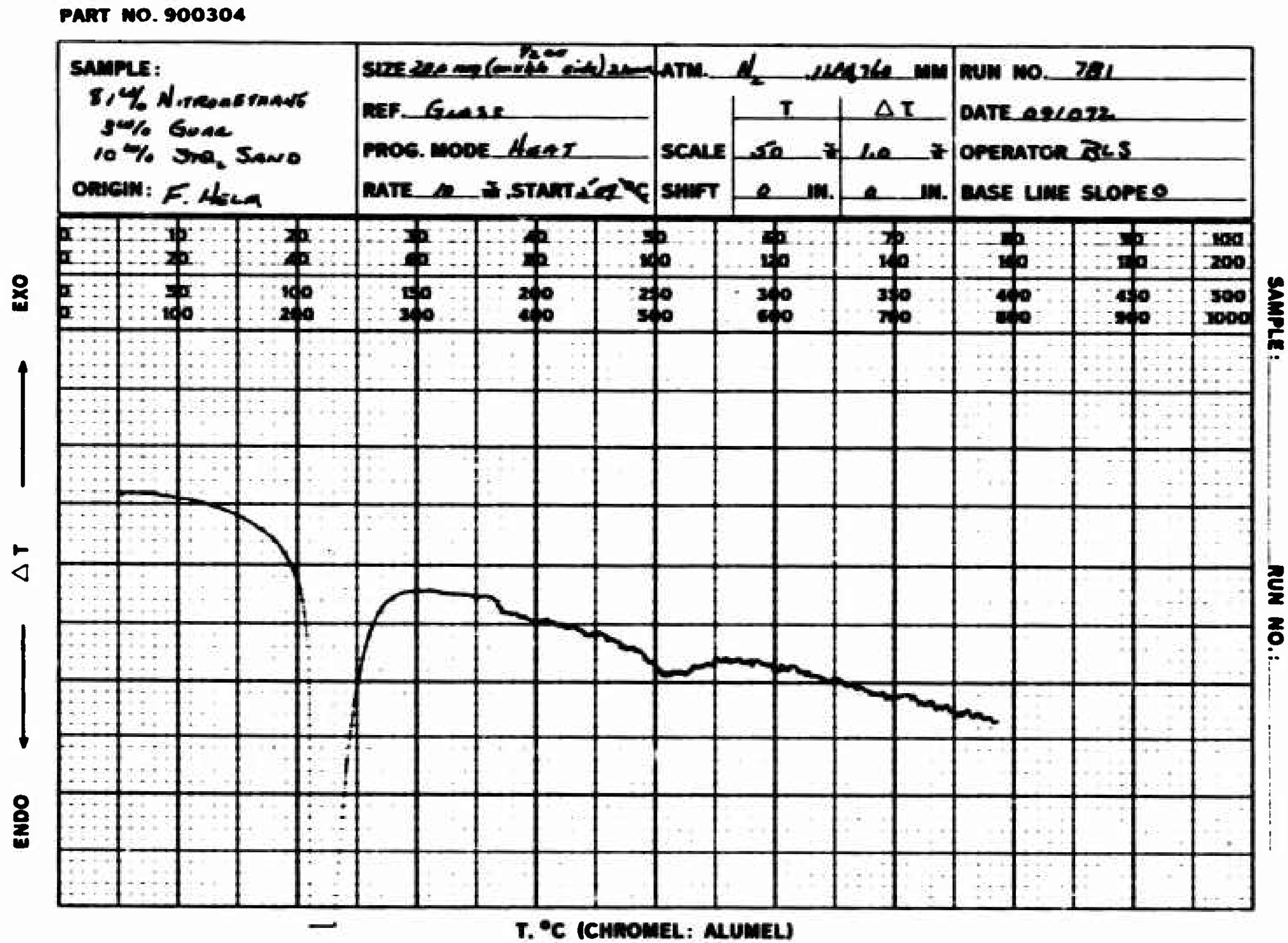

Figure 2.1 Differential thermal analysis of RX-01-AE.

Impact sensitivity was determined on the LLL drop hammer. Runs using techniques for both solid and liquid explosives failed to show reaction at the limiting height of 1.77 m (69.7 in.) using a 2.5-kg (5.52-lb) weight. Ignition tests revealed that a Tesla coil will ignite milligram samples of RX-01-AE if the spark gap is carefully adjusted. Larger samples, ignited by match, burn with a low blue flame until completely consumed.

2.2.2 Shock Sensitivity Tests

Duplicate tests were performed to determine the sensitivity of RX-01-AE to a No. 8 blasting cap, using 100-g (0.22-lb) samples of the HE placed in plastic cups positioned on lead bricks. The blasting cap was suspended just above the surface of the explosive and detonated. No reaction from the HE was obtained in either test.

Gap tests were conducted to compare the sensitivity of RX-01-AE to both unsensitized nitromethane and nitromethane that had been sensitized by the addition of 5 wt% ethylenediamine. Nitromethane so sensitized can be reliably initiated with a No. 8 blasting cap.

The test configuration was chosen for convenience, and test results cannot be compared to those that would be obtained with the ASTM card gap test. The tested samples were 8.5 mm (0.33 in.) × 25.4 mm (1.0 in.) long and confined in 8.5 mm (0.33 in.) of mild steel. The donor system was PBX-9404, 8.5 mm (0.33 in.) in diameter × 7.6 mm (0.30 in.) long, with a type K detonator. The inert barrier was brass. Results are presented in Table 2.1.[4]

Unlike commercial nitromethane and sensitized nitromethane, which display relatively clear cut go or no-go behavior, RX-01-AE reacts in varying degrees over a range of gaps. Accordingly, the 50% point for RX-01-AE is shown as a range in Table 2.1. The results indicate that RX-01-AE is only slightly more shock-sensitive than unsensitized nitromethane.

Table 2.1. Gap test results for commercial nitromethane, sensitized nitromethane (95 wt% nitromethane with 5 wt% ethylenediamine), and RX-01-AE.

	Density		Gap, 50% point		95% confidence interval	Number of shots
	(g/cm^3)	(lb/ft^3)	(mm)	(in.)		
Commercial nitromethane	1.13	70.5	0.38	1.5×10^{-2}	±0.13	11
Sensitized nitromethane	1.12	69.9	3.66	0.14	±0.13	11
RX-01-AE	1.21	75.5	0.8-1.3	3.1×10^{-2}- 5.1×10^{-2}	–	14

2.3 Explosive Performance

The detonation parameters of RX-01-AE were determined in the LLL cylinder test.[5] The major problem in preparing the cylinder test was to eliminate entrapped air introduced into the explosive during mixing and transfer operations. Normal loading operations for paste explosives, which deaerate by vacuum, were not appropriate because of the relatively high vapor pressure of nitromethane. The cylinder was successfully loaded by carefully avoiding the introduction of air into the explosive during mixing and loading. It was also necessary to place the guar gum in a desiccator under aspirator vacuum for several hours to remove adsorbed air. Without this treatment, air bubbles would form and grow in what at first appeared to be an acceptable cylinder loading.

Special equipment was built to load the cylinder (Figure 2.2). A 1 350-ml (1.4-qt) mixing vessel was constructed with a nipple on the bottom sized for 6.4-mm-i.d. (0.25-in.) plastic hose and a beveled upper edge to accept a piston easily. During the mixing operation the nipple was plugged and the piston removed. The nitromethane and sand were strongly agitated to form a vortex, and the guar gum was added as quickly as it would wet without lumping. The mixer was then stopped abruptly for several seconds to allow escape of trapped air before the gel formed. Mixing was resumed at a moderate level until

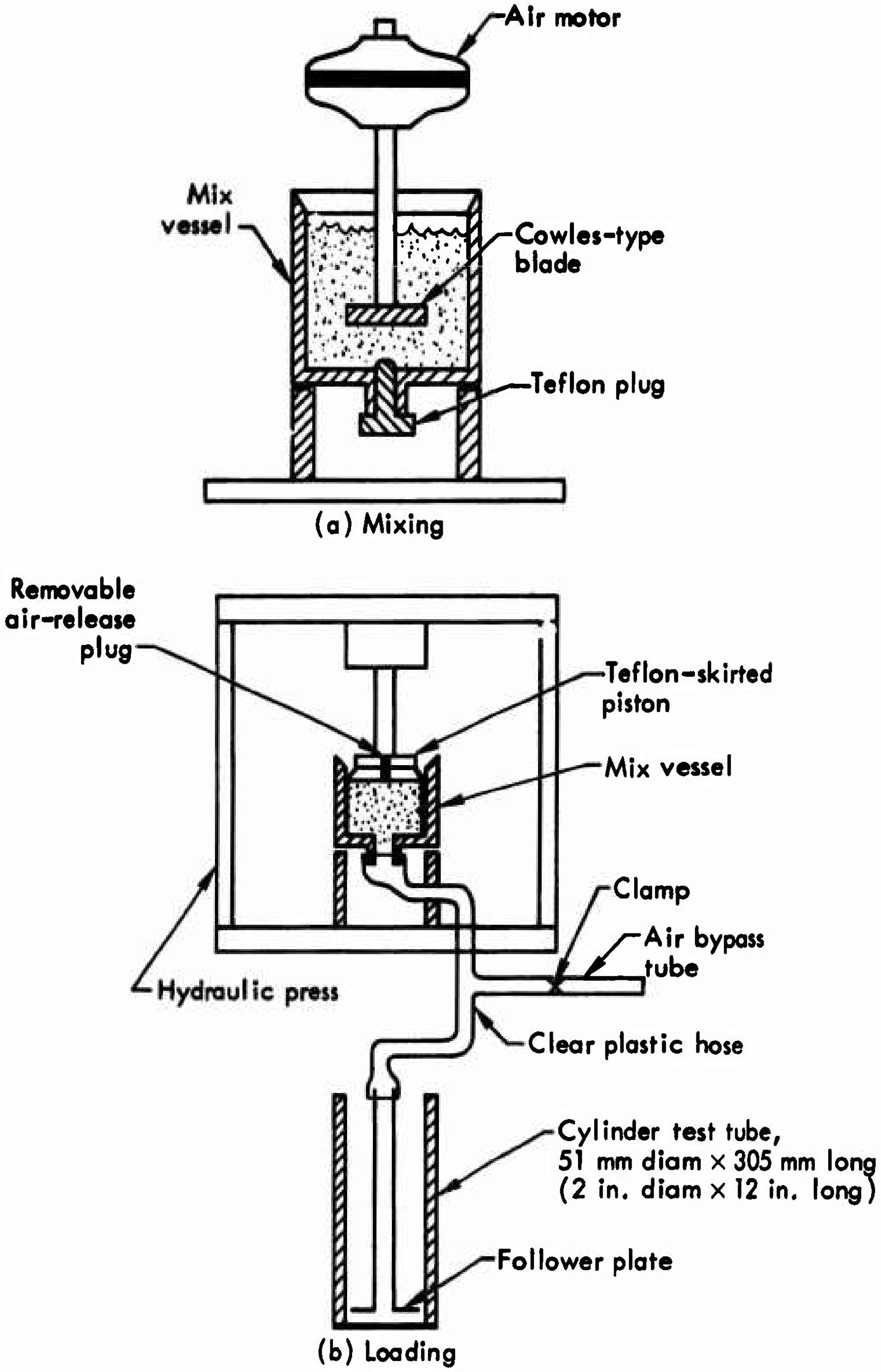

Figure 2.2 Mixing and loading equipment for cylinder test of RX-01-AE.

gelling was complete. Total mixing time for the 1-kg (2.2-lb) batch was about a minute.

The mixer motor and blade were removed, and the vented piston was pushed down to the surface of the explosive. The vent hole in the piston was then plugged and the assembly was placed in a hydraulic press, which pushed the piston (see Figure 2.2b).

A clear plastic hose was attached to the nipple on the mix vessel's bottom and to a 6.4-mm-o.d. (0.25-in.) thin-wall metal tube about 350 mm (14 in.) long. A round follower plate attached to the other end of the metal tube had a diameter of about 1.6 mm (0.06 in.) less than the 50.8-mm (2.0-in.) diameter of the copper cylinder to be loaded. This plate was lowered to the bottom of the cylinder, where it served to guide the explosive entering from the center loading tube to the inner cylindrical surface. This technique helped to exclude air during the loading. The plate followed the rising level of explosive, allowing the progress to be monitored. The clear plastic loading tube was tied with an air bypass tube that was normally clamped shut. By unclamping the bypass tube, any air that was seen entrained with the explosive could be bled away from the filling cylinder.

The loading procedure was first attempted with a glass tube of the same general dimensions as the test cylinder. No air bubbles could be visually detected. The test cylinder was then loaded. The density of both loadings was calculated by weight and volume determinations to be 1.21 g/cm^3 (75.5 lb/ft^3), which is very near theoretical density for the composition.

A summary of the cylinder performance of RX-01-AE compared with pure nitromethane is presented in Table 2.2. These data and the information obtained from the field tests are combined later in the report to obtain an EOS.

2.4 Rheology

Because of the cold weather anticipated in the Montana test area, the effect of temperature on mixing time and flow properties was determined. The gelling time and viscosity were checked at 273 K

Table 2.2 Cylinder test performance of RX-01-AE and nitromethane high explosives.

	RX-01-AE	Nitromethane
At 6-mm (0.23-in.) expansion:		
Elapsed time (μs)	7.92	7.51
Wall velocity (km/s)	1.00	1.06
Energy relative to nitromethane (%)	89	–
At 19-mm (0.75-in.) expansion:		
Elapsed time (μs)	19.68	18.71
Wall velocity (km/s)	1.17	1.22
Energy relative to nitromethane (%)	92	–

Table 2.3 Viscosity of RX-01-AE at 273 K and 291 K (0 and 18°C).

Shear rate (s^{-1})	Viscosity, Pa·s (10^{-3} cP)[a]	
	At 273 K (0°C)	At 291 K (18°C)
3.26	99.5	72.8
6.53	53.3	44.8
9.80	37.0	33.5
19.6	18.9	18.2
29.4	12.5	11.8
58.8	6.4	6.0
88.2	4.2	4.0
176.3	2.3	2.1
264.5	1.5	1.4
326.5	0.7	0.7

[a]The abbreviation cP is for centipoise.

(0°C) and found similar to values obtained at room temperature (see Table 2.3).

SECTION 3
EXPLOSIVE PROCESSING FOR PROJECT DIAMOND ORE SHOT IT-6

3.1 Selection of Mixing and Pumping Equipment

From the results obtained in the preliminary experiments, RX-01-AE was considered to be suitable for a planned 907.1-kg (1-ton) cratering shot in Montana. Next, the selection of mixing and pumping equipment capable of loading the 907.1-kg (1-ton) charge in a reasonable period of time was considered. Several approaches were studied and the simplest, least expensive safe system was chosen.

Air-driven equipment was selected because of its inherent safety in processing explosives. A standard open-ended 55-gal drum was used as the mix vessel. A 181-kg (400-lb) batch was mixed by means of an air motor, temporarily clamped to the barrel rim, which drove a three-bladed, 200-mm (7.9-in.) diameter propeller located on the end of a 1 m (3.28 ft) long shaft.

The Gengel-512 and sand must be uniformly suspended in nitromethane for approximately 1 min before the gel has attained sufficient viscosity to prevent the sand from settling. At that time, even though the mixer blade is turning, all visible mixing action has ceased. The gel continues to form, reaching 95% of its viscosity in 1 h and finally taking on a consistency similar to light custard. It will not retain a shape, but it resists being poured.

After the mixing action had stopped, the air motor was removed and the barrel was pushed under a barrel pump, particularly well-suited for pumping this viscous material. The barrel pump consisted of a frame that lowered a large piston, called a ram, into the 55-gal drum. Air cylinders on the frame forced the ram down onto the surface of the explosive and provided a positive inlet pressure of about 6.89×10^3 Pa (1 psi) to a conventional piston pump located on top of the ram. A pump discharge pressure of approximately 8.61×10^7 Pa (125 psi) was required to force 5×10^{-4} m^3/s (8 gal/min) of the gel through 10.7 m (35 ft) of 38-mm (1-1/2-in.)-i.d. natural rubber-lined fire hose.

3.2 Mixing and Loading the Charge

The processing equipment was brought to the Diamond Ore test site in Montana in a pickup truck (Figure 3.1). A lift truck was not available at the site to lower the 240-kg (530-lb) barrel pump to the ground; therefore, mixing and pumping operations were carried out in the bed of the truck. Even under these less than ideal conditions a total mix and pump time of only 2 h was required to fill the charge cavity. By performing mixing and pumping operations at the same time and providing faster nitromethane transfer to the mix drums, this equipment could produce more than 907 kg (1 ton) of RX-01-AE per hour. The use of a straight-sided, rather than ribbed, 55-gal mix drum would improve operation of the barrel pump. The ram cannot seal against the barrel wall when it passes ribbed areas, so explosive squeezes past and onto the top surface of the ram. The ram also tends to catch in the ribs when the barrel is being removed from the pump.

The barrel pump was disassembled several months after loading Shot IT-6. Moving parts and leather seals were in good condition due in part to pumping several gallons of diesel oil soon after loading the shot. Sand in the explosive had not scored the cylinder wall. Two heavy steel balls are used as valves in this pump. It is recommended that they be changed to a softer material, such as tetrafluoroethylene. The steel spacer between the two leather piston seals should be machined to reduce the outside diameter by 0.76 mm (0.030 in.). This machining will minimize the possibility of metal-to-metal contact in the event that the leather seals wear excessively.

3.3 Shot Results

The test shot, IT-6, was successfully fired using a 0.45-kg (1-lb) C-4 booster. Shot IT-6 was instrumented with a piezoelectric pin rate stick. The general shot layout is shown in Figure 3.2. A summary of detonation velocity information is presented in Table 3.1.

The average detonation velocity over a 300-mm (11.8-in) path was 6.14 km/s (0.24 in./μs), which compares favorably with the 6.11-km/s (0.23-in./s) velocity obtained from the cylinder test.

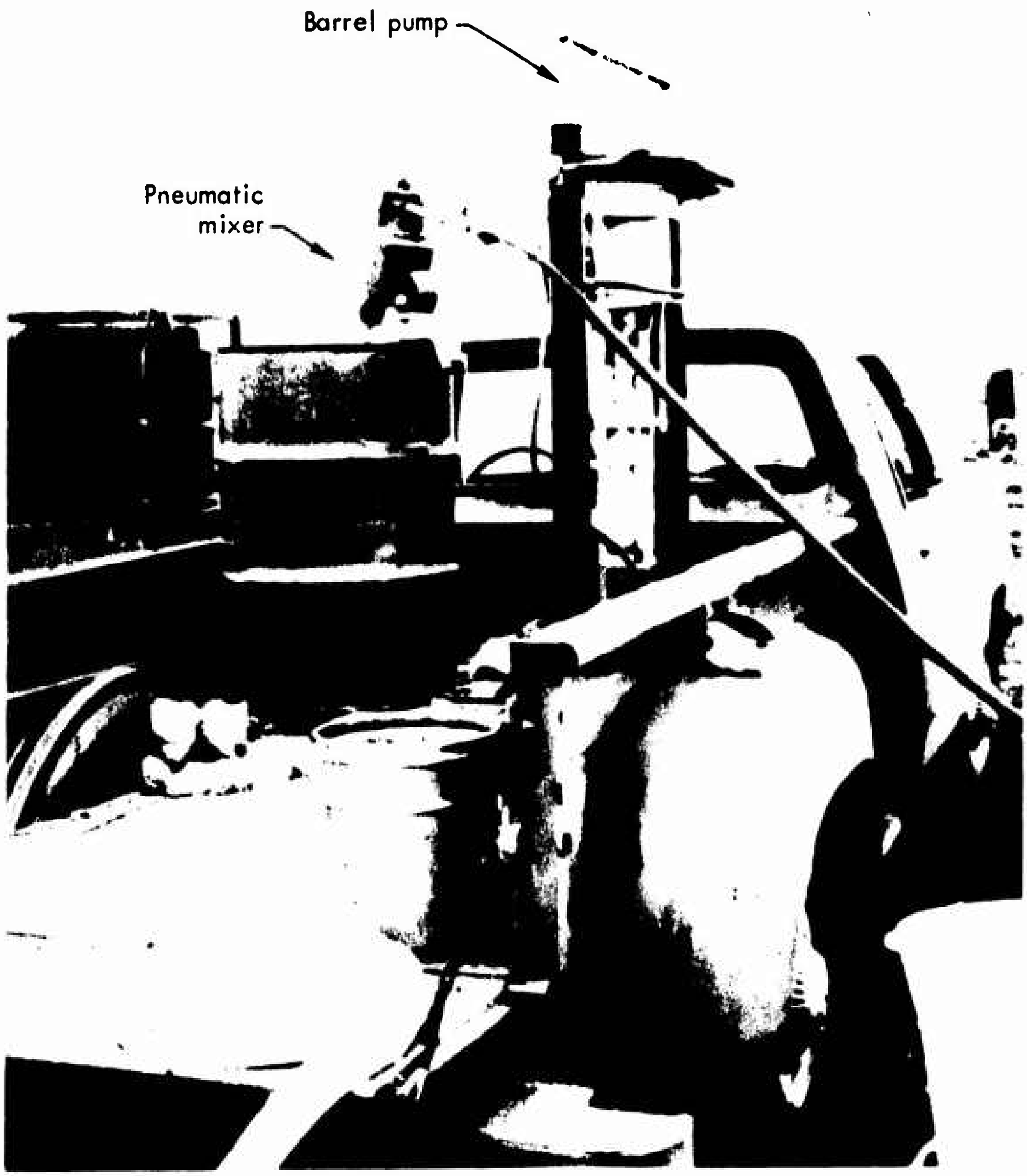

Figure 3.1 Mixing and loading equipment for Project Diamond Ore mounted on pickup truck.

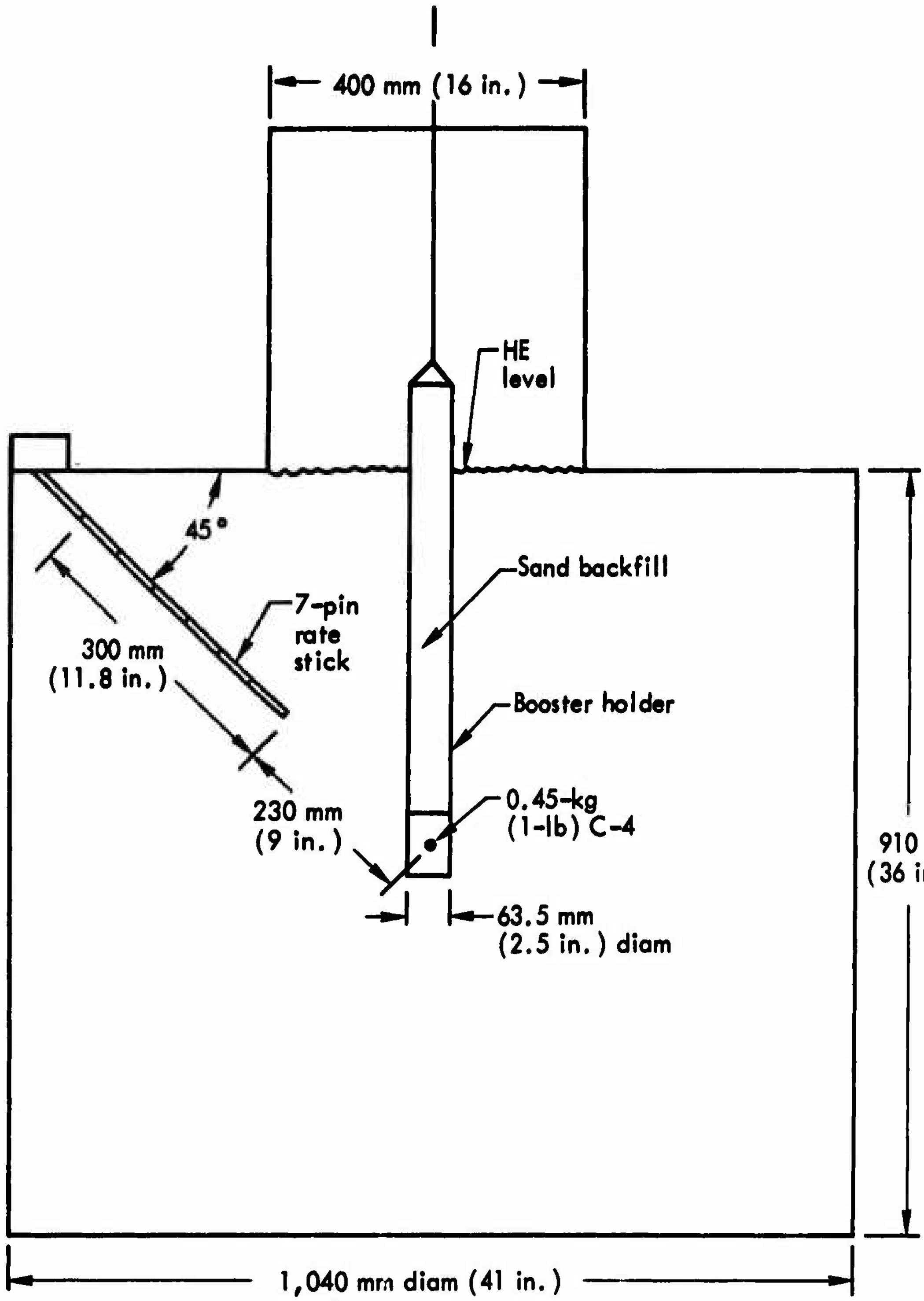

Figure 3.2 Charge configuration for IT-6 test shot, Project Diamond Ore.

Table 3.1 Detonation velocity information obtained from Diamond Ore Shot IT-6.

Pin increment	Time, Δt (μs)	Distance, ΔL (mm)	(in.)	Velocity, D (km/s)	(in./μs)
1-3	16.40	98.7	3.85	6.02	0.23
3-4	8.51	51.2	1.99	6.02	0.23
4-5	7.78	51.4	2.00	6.61	0.26
5-6	7.92	49.7	1.94	6.28	0.24
6-7	8.28	49.2	1.92	5.94	0.23
1-7	48.89	300.2	11.7	6.14	0.24

SECTION 4
EXPLOSIVE PROCESSING FOR PROJECT ESSEX

4.1 Equipment Changes for Handling Larger Quantities

The results obtained from Shot IT-6 were encouraging, and RX-01-AE was accepted as the explosive for Project ESSEX, Phase 1. Four cratering experiments were to be conducted in this program (see Table 4.1). Because of the large amount of explosive required for these shots, an investigation was begun of processing equipment more adequately sized to the task. Of primary concern was the pump. Pressure pulses created by the barrel pump were considered nonhazardous

Table 4.1 The four shots planned for Project ESSEX, Phase 1, using RX-01-AE explosive.

Shot	Depth of burial (m)	(ft)	Emplacement condition
12 MS	12	39.4	Stemmed
12 MPS	12	39.4	Partially stemmed
6 MS	6	19.7	Stemmed
6 MU	6	19.7	Unstemmed

when it was operated below 0.7-MPa (100-psi) outlet pressure. Even so, reduction or elimination of these pulses would be a desirable goal. We tested the Challenge Squeeze-Crete Model 120 pump, which is employed commercially to move concrete from a ready-mix truck to its point of use. It is a rotary pump using rollers to bear on and progressively flatten a heavy rubber hose [51-mm (2-in.) i.d.], which contains the material to be moved. The space surrounding the pump tube is evacuated to a pressure of approximately 10 kPa to 13.5 kPa (3 to 4 in.) of Hg, which in effect places a priming pressure of nearly an atmosphere on material in the feed hopper. This is a particular advantage when viscous materials are pumped. The pressure pulses created by this pump are much less severe than those of the barrel pump. In tests with the pump revolving at approximately 3.14 rad/s (30 rpm), 90 kg/min (200 lb/min) of RX-01-AE was pumped through 15 m (50 ft) of 38-mm (1-1/2-in.)-i.d. fire hose at a discharge pressure of 0.34 MPa (50 psi). The maximum output of the pump using the same hose was 225 kg/min (500 lb/min) at a discharge pressure varying from 0.5 to 0.7 MPa (75 to 100 psi). The Challenge pump was considered adequate and safe for the task.

Attention turned to the mixing step and assembly of the equipment. The mix drum was scaled up to accommodate a 520-kg (1 150-lb) batch and a 3-hp mixer. A platform was designed to mount the mixing equipment, Challenge pump, a 3.7-kW (5-hp) piston-operated air motor to drive the pump, and the vacuum pump. The platform top also served as a convenient work area for handling and dumping drums. All of the equipment was air-operated and required a total air volume of less than 7 m^3/min at 0.7 MPa (250 ft^3/min at 100 psi). A photo of the assembled equipment is shown in Figure 4.1.

4.2 Mixing and Loading the Charges

In the field operation, a batch consisted of two drums — totaling 453 kg (1 000 lb) — of nitromethane, 52.1 kg (114.9 lb) of iridium-treated sand, which was preweighed and packaged in 5-gal paint buckets, and 15.6 kg (34.5 lb) of guar gum, weighed as used.

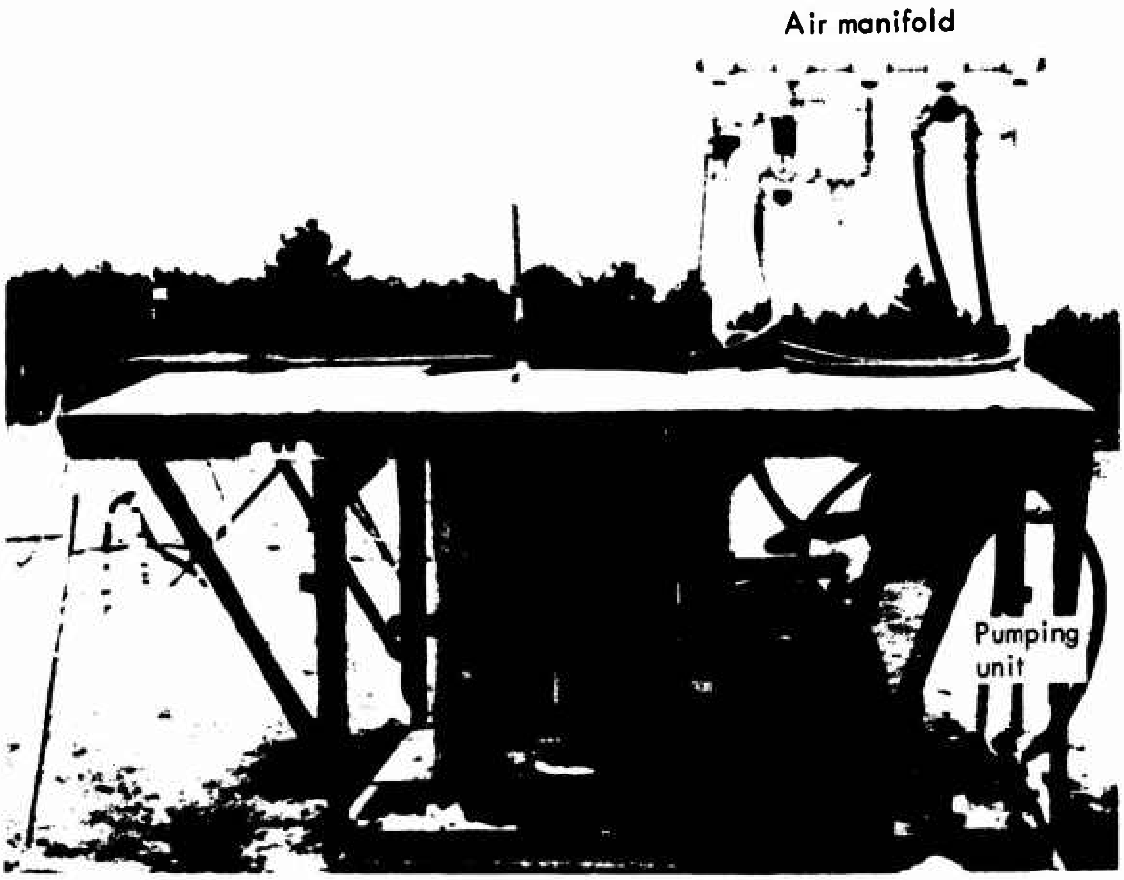

Figure 4.1 Platform used for mixing and loading of Project ESSEX charges.

In the process, both drums of nitromethane were dumped into the mixing tank. The mixer motor was started, the sand added, and then the guar gum. Mixing continued for about a minute. The mixer was then stopped, and the pumping operation started. The pump turned 3.14 to 3.66 rad/s (30 to 35 rpm) and required 0.18 to 0.21 MPa (26 to 30 psi) air pressure for this speed. A batch cycle averaged 3 min for pouring and mixing, and 5 min for pumping. The production rate was approximately 1.07 kg/s (4.25 tons/h).

4.3 Shot Results

The detonation monitoring system for the first ESSEX shot, 12 MS, consisted of two multipin rate sticks and two peak pressure gages. The arrangement shown in Figure 4.2 was employed to observe detonation symmetry. The remaining shots, 12 MPS, 6 MS, and 6 MU, were monitored with only the top rate stick and no pressure gages. For unknown reasons the rate stick in Shot 6 MU failed to report. Time measurements between pins were made with raster scopes. With the exception of the lower rate stick of Shot 12 MS, an overall time between widely separated pins was obtained using a time interval meter (TIM).

Detonation velocity information is presented in Table 4.2. The detonation velocity observed for RX-01-AE in the cylinder test was 6.11 km/s (0.238 in./μs) for the 907.1-kg (1-ton) Shot IT-6 it was 6.14 km/s (0.242 in./μs), and for the multiton Shots 12 MS, 12 MPS, and 6 MS it was an average of approximately 6.21 km/s (0.244 in./μs). It is believed that this trend toward higher velocity is related to increasing shot size.

Plastic gage transducers were installed to measure peak detonation pressures.[6] Signals shown in Figure 4.3 are pressures in the plastic gage material. An estimated detonation pressure of 1.2×10^{10} Pa (120 kbar) in the explosive was derived from this information after corrections for the divergent wave character of the shock and gage response. The symmetry of the explosion appears to be excellent.

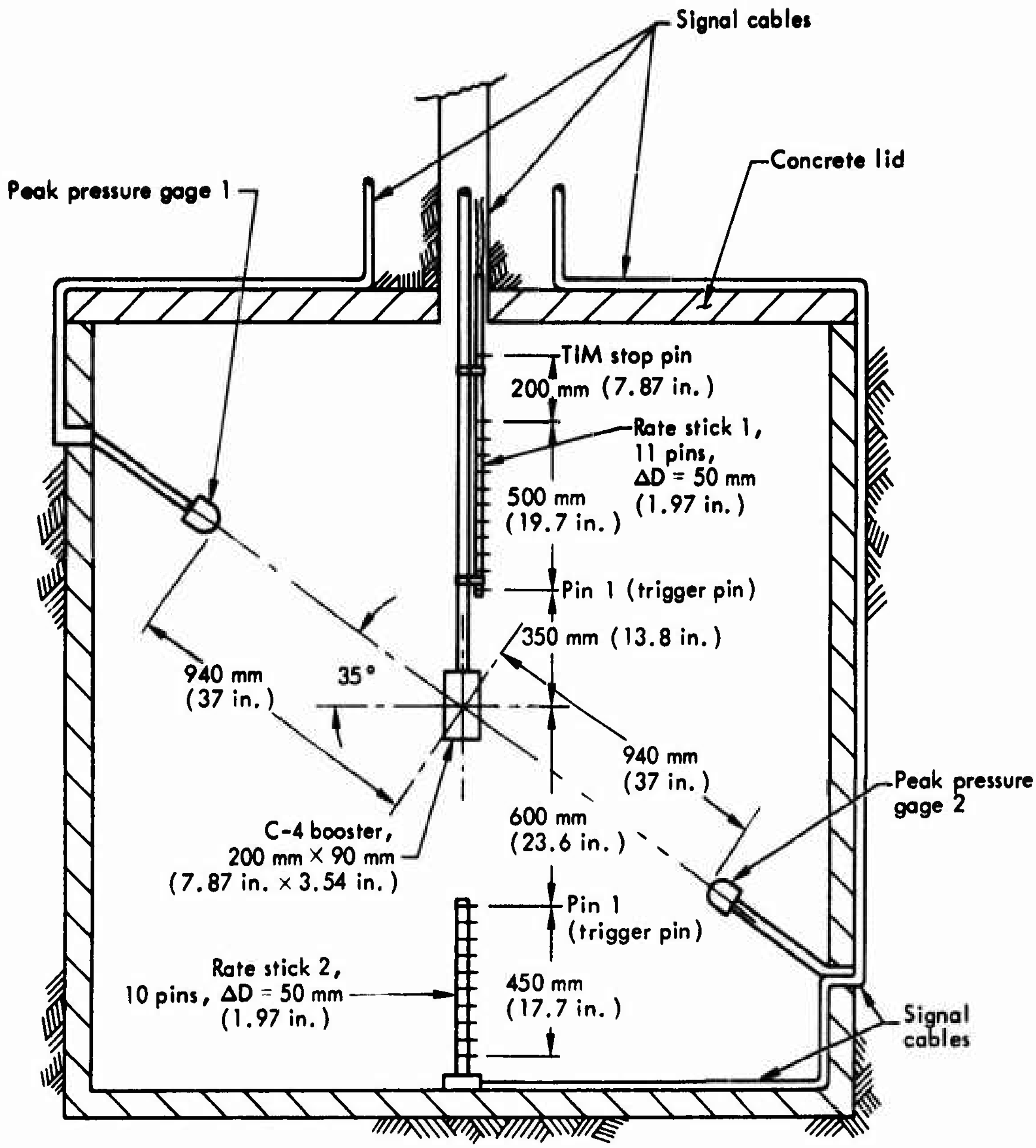

Figure 4.2 Detonation monitoring system for Project ESSEX.

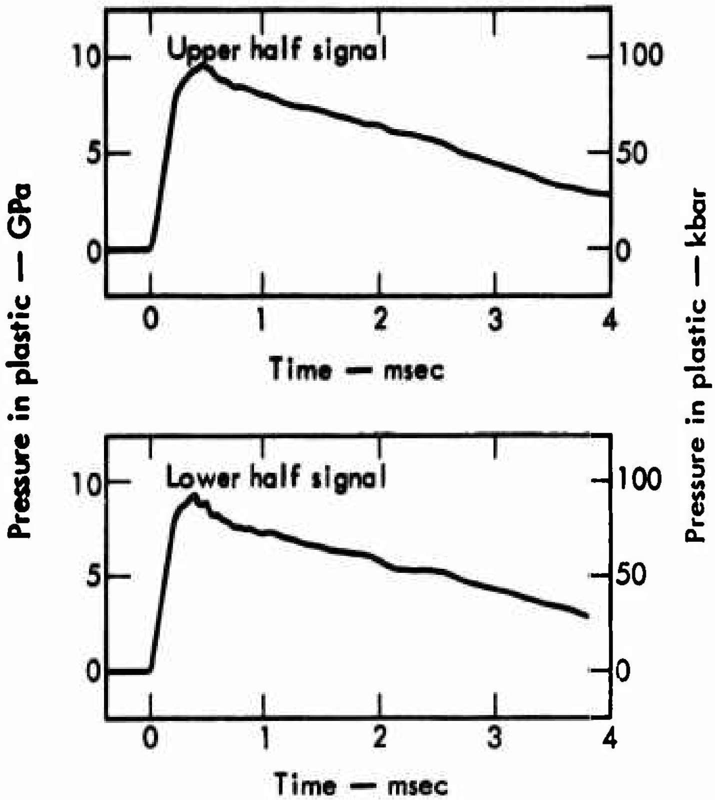

Figure 4.3 Plastic gage signals from upper and lower halves of Shot 12 MS, Project ESSEX.

Table 4.2 Detonation velocity information obtained from Project ESSEX Shots 12 MS, 12 MPS, and 6 MS.

Pin increment	Shot 12 MS (top rate stick) Distance, ΔD (mm)	(in.)	Time, Δt (μs)	Velocity, D (km/s)	(in./μs)	Shot 12 MS (bottom rate stick) Distance, ΔD (mm)	(in.)	Time, Δt (μs)	Velocity, D (km/s)	(in./μs)
1-2	49.0	1.91	8.18	5.99	0.233	50.0	1.95	8.13	6.15	0.240
2-3	50.5	1.97	8.28	6.10	0.238	48.0	187	7.87	6.10	0.238
3-4	49.0	1.91	7.94	6.17	0.240	52.0	2.03	8.13	6.40	0.250
4-5	50.0	1.95	8.06	6.20	0.242	49.0	1.91	7.87	6.23	0.243
5-6	51.0	1.99	8.24	6.19	0.241	50.0	1.95	7.88	6.35	0.247
6-7	48.0	1.87	7.54	6.37	0.248	47.0	1.83	7.66	6.14	0.239
7-8	49.0	1.91	7.55	6.49	0.253	53.0	2.07	8.44	6.28	0.245
8-9	51.0	1.99	8.36	6.10	0.238	50.0	1.95	8.14	6.14	0.240
9-10	50.0	1.95	—[a]	—	—	49.0	1.91	7.88	6.22	0.242
10-11	50.0	1.95	15.84	6.31	0.248					
1-11	497.5	19.4	79.99	6.22	0.243	448.0	17.5	72.0	6.22	0.242
1-12 (TIM)[b]	711.5	27.7	115.1	6.18	0.235			(pin increment 1-10)		

Pin increment	Shot 12 MPS (top rate stick) Distance, ΔD (mm)	(in.)	Time, Δt (μs)	Velocity, D (km/s)	(in./μs)	Shot 6 MS (top rate stick) Distance, ΔD (mm)	(in.)	Time, Δt (μs)	Velocity, D (km/s)	(in./μs)
1-2	50.0	1.95	8.20	6.10	0.238	51.0	1.99	8.46	6.03	0.235
2-3	49.0	1.91	8.00	6.13	0.239	49.0	1.91	7.76	6.31	0.246
3-4	49.0	1.91	8.00	6.13	0.239	50.5	1.97	8.04	6.28	0.245
4-5	49.5	1.93	8.02	6.17	0.241	49.5	1.93	7.92	6.25	0.244
5-6	50.5	1.97	8.26	6.11	0.238	51.0	1.99	8.16	6.25	0.244
6-7	48.0	1.87	7.84	6.12	0.239	50.0	1.95	8.00	6.25	0.244
7-8	52.0	2.03	8.46	6.15	0.240	49.0	1.91	7.94	6.17	0.240
8-9	48.5	1.70	7.82	6.20	0.217	51.0	1.99	8.20	6.23	0.243
9-10	53.0	2.07	8.48	6.25	0.244	49.0	1.91	8.30	5.90	0.230
10-11	52.0	2.03	8.14	6.39	0.249	51.0	1.99	7.50	6.80	0.265
1-11	501.5	19.6	81.22	6.17	0.241	501.0	19.5	80.28	6.24	0.243
1-12 (TIM)	709.5	27.7	114.2	6.21	0.242	715.0	27.9	114.7	6.23	0.243

[a]Pin 10 didn't report.

[b]TIM = time interval meter.

The charges were detonated by a centrally located booster containing 1.6 kg (3.5 lb) of C-4 explosive in a thin-wall aluminum can 89 mm (3.5 in.) in diameter. The booster was initiated by a boosted Reynolds RP-1 detonator (electric bridge-wire type). Detonator cable lengths were 64 m (210 ft) of C cable, running to the remotely

controlled capacitor discharge unit (CDU). The CDU was well-protected and survived all shots even though deeply covered by ejecta.

SECTION 5
EQUATION OF STATE FOR RX-01-AE

From the cylinder test and field data an EOS for the detonation products was obtained, using the Jones-Wilkins-Lee (JWL) form of the EOS, which accurately describes the pressure-volume-energy behavior of the detonation products of explosives in metal acceleration applications. The equation is

$$P = A\left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E}{V}.$$

The equation for P as a function of V at constant entropy (i.e., the isentrope) is

$$P_s = Ae^{-R_1 V} + Be^{-R_2 V} + CV^{-(\omega+1)},$$

where

$$V = \frac{\text{volume of detonation products}}{\text{volume of undetonated explosive}}$$

P = pressure in megabars (Mbar)

E = Mbar-cm^3/cm^3

The EOS parameters obtained for RX-01-AE explosive are presented in Table 5.1.

Table 5.1 Equation-of-state parameters for RX-01-AE explosive.

1. <u>CJ state</u>	
ρ_0	1.21 g/cm^3
P	0.120 Mbar
D	6.21 mm/μs
E_0	0.045 Mbar-cm^3/cm^3
T	2.889
V^{CJ}	0.723
2. <u>JWL coefficients</u>	
B^1	3.180
B^2	0.063 78
R^1	4.9
R^2	1.4
ω	0.38
C	0.009 261

SECTION 6
CONCLUSIONS AND RECOMMENDATIONS

The work outlined in this report has demonstrated that gelled nitromethane is a practical explosive for cratering experiments involving the suspension of 10 wt% sand. The performance of the explosive formulation RX-01-AE in several multiton shots was predicted closely by the results of a standard LLL 50.8-mm (2-in.) cylinder test. Prior to the firing of a cylinder shot, performance predictions were made using information from dilute nitromethane systems tested in the past. Because of the good agreement observed in all of this work it is believed that RX-01-AE is a reproducible and reliable explosive. Therefore, it is believed that this explosive or a modification of it may find use in future large-scale field experiments.

RX-01-AE, like nitromethane, is sensitive to initiation by adiabatic compression. If in the future it is necessary to pump RX-01-AE at discharge pressures higher than those used in the work reported here, additional testing should be undertaken to assure the safety of the operation.

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